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ENVIRONMENTAL FLOW AND REJUVENATION OF RIVER GANGA

REJUVENATING KALI RIVER IN UTTAR PRADESH – A CASE STUDY OF RIVER FLOWS ENHANCEMENT THROUGH AGRICULTURE WATER MANAGEMENT

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The known large river systems gain might and prominence through the contributions of numerous smaller tributaries, streams, rivulets, and healthy aquifer systems. These freshwater systems, not only support the flows in the large rivers but also build and strengthen the very character of such large rivers. They support them in extending various services to nature and the people. Various biotic and abiotic components are dependent upon the healthy state of these freshwater systems. Kali River, one such tributary of the mighty River Ganga originates in Muzaffarnagar (Uttar Pradesh) and joins the Ganga River in Kannauj district of Uttar Pradesh. During 420 plus km of the river course, the Kali faces several issues like – pollution from urban and industrial hubs, catchment fragmentation, over-abstraction of both surface and groundwater coupled with low water use efficiencies in agriculture, which uses almost 80% of freshwater, making the flows leaner with degraded water quality. Despite this, the Kali River with a catchment area of 9400 km^2, is one of the critical tributaries of the Ganga River. The restoration of freshwater flows in a river can be achieved through diverse strategies. Whilst, one of the most talked about approaches is releases from dams and barrages; however, other crucial approaches, such as optimized agricultural water management, can significantly reduce water usage (canal and groundwater withdrawals). In irrigation canal systems, the available and saved water through demand and supply side management in canal command areas can be routed through the passage from the tail-ends of the canals to the nearby rivulets and drains or ponds, thereby enhancing flows. This approach offers dual benefits: rejuvenated ponds enhance year-round water security for riparian community and flows released into river systems improves hydrological health of rivers.

A 3-year journey of Kali River flows enhancement which commenced in 2020, was implemented through multi-stakeholder-led collective actions by 40,000 farmers of command area farmers through their respective Water Users Associations (WUA), Uttar Pradesh Irrigation & Water Resources Department, the Kasganj District Administration and World-Wide Fund for Nature India. A three-pronged approach was adopted to demonstrate the hydrological gains in Kali River: (a) Demand-side interventions – reducing irrigation water application thereby improving the water use efficiencies. In this regard, various package of practices pertaining to agriculture water management was promoted, demonstrated and implemented across the crops of wheat and maize in the command area. This included line sowing, application of bio-fertilizers, bio-pesticides and micronutrients; (b) Supply Side Interventions – rehabilitating the irrigation canal infrastructure and rejuvenating/creating the passage from the tail-end of the canals with the nearby drains/rivulets/ponds. This work included the rehabilitation of the entire canal system comprising of the installation of metal

gates at the heads of all 10 canals to ensure better water regulation across canals, installation/rehabilitation of outlet heads, rehabilitation/construction of gauges (pansaal) near head and tail of the canal, construction/rehabilitation of tail-fall and passage to connect the canal tail end to nearby river/rivulet bank; (c) Institutional strengthening – awareness, mobilization, and capacity strengthening of existing WUAs in the command area. This work included in-room training on guidelines and provisions of prevailing legislations on Participatory Irrigation Management, exposure and knowledge-exchange activities across the areas of active WUAs in the state and the country.

As part of this initiative (till June 2024), with the support of command area farmers, over 2 billion liters of saved and available water from the command areas of 10 irrigation canals (08 Minors and 02 Distributaries) of the Bachhmai Distributary Canal System (part of Farrukhabad Branch Canal of Lower Ganga Canal system) is released into Kali River. This not only led to enhancing Kali River flows but also improved its assimilative capacity. Besides the enhancement of flows in the Kali River, on the agriculture front, the reduction in the input cost has been observed. Now the farmer's reliance on chemical inputs in reducing, as there is gradual reduction in chemical inputs application as bio-fertilizers and bio-pesticides are being promoted and demonstrated, as part of Demand-Side Management activities. The farmers are also trained on the preparation of these bio-products. This aspect complements Government of India's initiative on National Mission on Natural Farming (2023-26), *Paramparagat Krishi Vikas Yojana* and other such programmes. The farmers have also observed agricultural productivity gains while implementing various measures under the Demand Side Management. Another dimension of this initiative is engagement with the District Ganga Committee (DGC) Kasganj, wherein the Kali River initiative is presented, discussed, deliberated, and guided by various members of the DGC. A joint team led by DGC members having representation from district authorities, Uttar Pradesh Pollution Control Board, Uttar Pradesh Irrigation & Water Resources Department, concerned Water Users Associations, and WWF India, conducted a field survey to verify the on-ground status. This joint team concluded the same, i.e. the health of Kali River from the perspective of assimilative capacity is improving.

The Kali River initiative, documented in this paper, has the potential to act as a roadmap for flows enhancement in those rivers, which traverse through agrarian landscapes characterized by irrigation canal systems and low water use efficiencies in agriculture. On these lines, through similar multi-stakeholder-led approaches, the work is underway with over 200,000 farmers spread across 800 villages in 7 districts of Uttar Pradesh and Madhya Pradesh. The objective herein is to benefit the health of 7 small or large rivers (Kali, Karula, Gaagan, Ramganga, Parbati, Noon, Sindh). Whilst, the farmer, is always referred as the biggest user of freshwater; however, the Kali case study exemplifies and demonstrates how the very same farmer can support river rejuvenation programmes and projects. The approach discussed in this paper has the potential of upscaling and mainstreaming across canal water management, leading to revival of local freshwater resources.

Keywords: *Flows enhancement, irrigation, canal system, agriculture, Environmental Flows, Ganga River, Kali River*

ASSESSMENT OF THE ECOSYSTEM SERVICES OF A SEMI-ARID REGION OF INDIA

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Ecosystems worldwide are facing increasing pressures from human-induced activities, including climate change, habitat fragmentation, and nutrient pollution. These challenges significantly impact ecosystem functions and the services they provide, such as water quality, climate regulation, and agricultural productivity. Ecosystem services are vital for human well-being and sustainable resource management, underscoring the need for comprehensive assessment tools to understand their dynamics and inform effective management strategies. Water-related services, including water yield, purification, flow regulation and climate control, are particularly crucial for understanding basin-level ecological health. This study examines the spatiotemporal variations of ecosystem services within the Ken Basin, a key tributary of the Yamuna River in India, over the period 1985–2009.

The study used various data sets to run the Soil and Water Assessment Tool (SWAT) model, which simulates hydrological and ecological processes in the Ken Basin. Climatic data, such as daily precipitation and temperature, were used. Observed discharge data from the Banda gauging station (1985–2009) were used for model calibration and validation. Geospatial data, including Digital Elevation Models (DEMs), soil data, and land-use data were also incorporated to simulate the hydrological processes within the basin. The basin was divided into four subbasins, which were further subdivided into 698 Hydrological Response Units (HRUs). The model was calibrated for the period 1985-1995, resulting in a coefficient of determination (R^2) of 0.91 and a Nash-Sutcliffe Efficiency (NSE) of 0.88. Validation for the period 1996–2009 resulted in R^2 and NSE values of 0.84 and 0.83, respectively, indicating the model's dependability. After the SWAT model simulations were completed, the data were utilized to assess four key ecosystem services: water yield, purification, flow management, and climate control. These results were subsequently included into the Total Ecosystem Services (TES) index, which combines the performance of all four ecosystem services into a single statistic. The entropy weight method was used to determine the relative value of each service, with weights assigned based on its variability and significance. The entropy weights assigned to each ecosystem services were 0.19 for water yield, 0.236 for total nitrogen, 0.173 for total phosphorus, 0.249 for flow management, and 0.149 for climate control.

The results of the analysis showed that the Total Ecosystem Services (TES) index remained relatively stable, ranging from 0.8 to 0.9 over the 24-year study period. Water yield and climate control services showed decreasing trends, indicating the difficulties in preserving water supply and mitigating climatic variations. These changes are related to variations in precipitation patterns, evapotranspiration rates, and soil water dynamics, all of which influence streamflow and water supply. In contrast, ecosystem services related to purification

(total nitrogen and total phosphorus) and flow management showed increasing trends. The increase in purification services indicates rising nutrient loading in the basin's water systems, owing mostly to agricultural operations. The widespread use of nitrogen- and phosphorus-based fertilizers for agriculture has resulted in significant nutrient runoff into the river, especially during the monsoon season. Flow management services also increased, demonstrating the basin's ability to control water availability in response to changing climatic and anthropogenic stresses. However, increased nutrient loads caused by agricultural runoff put the basin's ability to sustain water quality at risk, emphasizing the significance of integrated water resource management measures. The study's findings emphasize the complex interaction of natural processes and human activities that affect ecosystem services. While water yield and climate control services are under significant pressure due to changing precipitation patterns and human activities, the increased nutrient and flow regulation services highlight the dynamic nature of ecosystem functions. These trends underscore the important need for sustainable land and water management strategies that prioritize the balance of ecosystem services, especially in the context of rising agricultural demands and climate variability. This study contributes to the broader understanding of ecosystem service dynamics in river basins and provides valuable insights for policymakers and resource managers. By integrating the SWAT model with entropy weight calculations, the study offers a robust framework for evaluating ecosystem services at the basin scale. The findings highlight the necessity of continuous monitoring and adaptive management in preserving ecosystem services and promoting sustainable development in the face of rising environmental and anthropogenic challenges.

The Ken Basin ecosystem services are changing significantly, with implications for water availability, quality, and management. The trends observed in this study highlight the importance of proactive strategies for addressing growing difficulties and ensuring the long-term viability of ecosystem services. Integrated approaches that integrate sustainable farming practices, efficient water resource management, and climate adaption strategies will be vital to the basin's ecological health and functionality. This study emphasizes the importance of ecosystem service assessments in guiding evidence-based decision-making and advancing the goals of sustainable development.

Keywords: *SWAT model, Total ecosystem services, Ken basin, entropy weight method, water yield, purification, flow management, climate control*

STREAM DYNAMICS ANALYSIS OF STRETCH OF GANGA RIVER USING GEO-SPATIAL TECHNIQUES

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The behavior of river systems is essential for comprehending the environmental processes that influence landscapes, eco-systems, and human communities. Rivers, such as the Ganga, are integral to the socio economic and cultural identity of the regions they flow through, particularly in India. This research aims at examining the stream dynamics of the Ganga River at Kanpur by utilizing Remote Sensing (RS) and Geographic Information System (GIS) methodologies. The main goal of this study is to evaluate changes in flow dynamics, meandering patterns, and the Entrenchment Ratio (ER) along the portion of the Ganga River that runs through Kanpur, covering the period from 1985 to 2021. The investigation uses satellite imagery and geo-spatial data to monitor the spatial and temporal changes in the morphology of the river and its ecological effects on the surrounding landscapes.

The area being studied encompasses a 39 km segment of the Ganga River, stretching from the Brahmavart Ghat (Latitude 26°36'49.62"N, and Longitude 80°16'28.83"E) to the Hanuman Temple at Dhori Ghat (Latitude 26°22'40.79"N, and Longitude 80°29'24.94"E), and is noted for its active river morphology and regional significance. The river flows in a north-to-south trajectory through varied landscapes that feature open fields, farmland and regions on the periphery of Kanpur city, Uttar Pradesh (India). The analysis period, which ranges from 1985 to 2021, reveals considerable changes in the path, width, and overall behavior of the river. Satellite data from 1985 to 2021 have been employed to digitize the full width of the bank, central flow lines, and Bankline of the Ganga River. These digitized features have then been compared across the years to identify changes in the flow dynamics of the river, meandering tendencies, and consequent changes in the ER. The analysis has been conducted at the interval of 3 km along the study stretch, providing a detailed view of how the course of the river has shifted over time.

The findings of the study indicate a marked shift in the flow of the river over the 36-year period. One of the most significant observations has been the continuous lateral movement of the river towards the left-hand side, particularly observed at a location approximately 13 km from the Brahmavart Ghat. At this location, the river has shifted by approximately 1.8 km from its original position in 1985. This movement has been especially prominent in open fields and agricultural land where the river has altered its course, potentially affecting both the local eco-system and human infrastructure. The research has observed also the widest point of the river as 4150 meters and the narrowest point as 190 meters. These differences in width reflect the ever-changing nature of the river, and point to the locations where bank erosion or sediment build-up could have influenced the path. The ER has reached a maximum of 98.31, indicating the river system that is highly entrenched. The Sinuosity Index, has peaked at 1.098, suggesting that the river displays a relatively low level of curvature despite showing notable meandering patterns.

The results of this study are a testament to the utility of Remote Sensing and GIS technologies in understanding the river dynamics. By using satellite imagery, the study was able to capture large-scale changes in the river’s morphology and track subtle variations that might otherwise go unnoticed. These findings are important for the management of the Ganga River, especially considering the increasing human settlement and agricultural activities along its banks. As the river continues to shift, the need for effective river management strategies becomes even more critical. The study emphasizes the importance of continuous monitoring and the integration of advanced RS and GIS technologies to track changes in river systems, predict future trends, and develop strategies for sustainable management.

The study also brings attention to the broader environmental and social implications of the river dynamics. The shifting course of the river can have significant consequences for local agriculture, water availability, and infrastructure. In particular, the areas of significant erosion or sediment deposition could face challenges related to flooding, loss of agricultural land, and displacement of communities. Furthermore, changes in the river's flow patterns could have ecological impacts, potentially altering habitats for aquatic species and affecting the overall health of the river eco-system. The study also points to the importance of taking proactive steps to mitigate the adverse effects of the river dynamics. As the Ganga River plays a vital role in the livelihood of millions of people, particularly in Uttar Pradesh, it is essential to implement measures that safeguard the river's integrity while minimizing human-induced impacts. These measures could include the construction of river training structures such as embankments and check dams as well as the implementation of policies that regulate land use along the riverbanks to reduce the risk of further erosion and encroachment.

In conclusion, this study demonstrates the effectiveness of using Remote Sensing and GIS technologies to assess the stream dynamics of the Ganga River at Kanpur. The analysis of flow dynamics, meandering and Entrenchment Ratio has provided valuable insights into the changing morphology of the river and the potential implications for local eco-systems and human activities. The findings underscore the importance of continuous monitoring and adaptive management strategies to ensure the long-term sustainability of this vital waterway. As such, the study calls for a concerted effort to mitigate the adverse impacts of the river dynamics and ascertain the sustainable use of the river resources for future generations. Given the rapid pace of environmental changes, this research also serves as a reminder of the necessity for interdisciplinary approaches that combine advanced technology with policy interventions to manage the river system effectively. The Ganga River with its immense cultural, ecological and economic significance requires careful and informed management to preserve its integrity for future generations.

Keywords: *Ganga, environment, entrenchment ratio, Brahmavart Ghat, remote sensing, morphology*

INTEGRATED ENVIRONMENTAL FLOW ASSESSMENT FOR THE SUBARNAREKHA RIVER: A HOLISTIC APPROACH TO SUSTAINABLE ECOSYSTEM MANAGEMENT

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The assessment of environmental flows (E-Flows) is crucial for the sustainable management of river ecosystems. Various methods have been developed to determine the E-Flows, ranging from hydrological records to sophisticated frameworks that incorporate ecological, hydraulic, and socio-economic considerations. This study focuses on the Subarnarekha River, an interstate river flowing through Jharkhand, Odisha, and West Bengal, with a particular emphasis on a holistic approach to E-Flow assessment that integrates hydrological, hydraulic, and habitat simulation methodologies.

The evolution of E-Flow assessment methodologies dates back to the 1940s, with initial efforts in the United States emphasizing minimum flow requirements. Over the time, methodologies have expanded, categorized into hydrological, hydraulic rating, habitat simulation, and holistic approaches. Hydrological methods rely on long-term streamflow data to estimate flow statistics, while hydraulic rating methods focus on the relationship between discharge and hydraulic parameters such as depth and velocity. Habitat simulation methods extend hydraulic approaches by linking physical conditions to habitat suitability for specific aquatic species. Holistic methods, developed in the 1990s, consider the entire aquatic ecosystem, incorporating diverse factors like hydrology, ecology, and socio-economic needs. Globally, over 240 methodologies have been identified for E-Flow assessment, demonstrating the complexity and adaptability of approaches to address site-specific challenges. Notably, the classifications by Tharme (2003) and others provide a structured framework for understanding these methodologies, emphasizing their applicability in different ecological and hydrological contexts. The present study employs a combination of hydrological, hydraulic, and habitat simulation methods for the Subarnarekha River. Long-term discharge data were analyzed using flow duration curves (FDC) and Indicators of Hydrologic Alteration (IHA). Hydraulic and habitat simulations were conducted using the HEC-RAS 1D model to establish depth-discharge relationships and evaluate flow requirements for maintaining suitable habitats for indicator fish species.

FDC analysis was used to assess hydrologic scenarios across different dependability years. For a 34-year period (1986–2019), the study identified critical flow thresholds such as Q90 and Q95, representing 90% and 95% probability of flow availability, respectively. These thresholds inform the baseline for maintaining ecological health. Additionally, the FDC provides insights into seasonal variations, particularly during lean months, highlighting intervals that influence riverine conditions and aquatic life. IHA analysis categorized flow conditions into five environmental flow components (EFCs): low flows, extreme low flows, high-flow pulses, small floods, and large floods. These EFCs highlight the ecological functions of various flow conditions, such as sustaining aquatic habitats, supporting biodiversity, and facilitating nutrient transport. By maintaining these flow components, the

study ensures the ecological integrity of the river system, emphasizing the interconnectedness of hydrological patterns and ecological processes. Hydrodynamic modeling using HEC-RAS provided insights into the flow-depth-velocity relationships at different river sections. Depth-discharge curves were developed to determine the flow requirements for maintaining specific water depths essential for the survival of the indicator species, *Bagarius bagarius* (Hamilton-Buchanan). This endangered fish species, known for inhabiting rocky pools and rapids, requires water depths of 0.25 to 1.5 meters and velocities ranging from 0.1 to 1.5 m/s. The study used HEC-RAS simulations to generate depth-discharge relationships for various locations along the river. Scenarios were modeled to maintain depths of 0.3m, 0.4m, and 0.5m during lean and monsoon seasons, ensuring ecological connectivity and suitable habitats for aquatic species. This approach highlights the critical role of hydrodynamic modeling in bridging data-driven assessments with ecological needs.

The results highlight the critical discharge values required to sustain ecosystem health at different river locations. For location 1 (13.66 km downstream), 2.15 cumec discharge is required for maintaining a depth of 0.4 m. Similarly, 0.77 cumec discharge is necessary for maintaining same depth at location 2 (16.30 km downstream). The recommended E-Flow regimes for the Subarnarekha River account for seasonal variations and habitat requirements, balancing ecological sustainability with water resource management. The analysis underscores the importance of adaptive flow regimes that cater to varying ecological and hydrological demands across different locations. This integrated approach to E-Flow assessment has significant implications for the sustainable management of the Subarnarekha River. By aligning hydrological, hydraulic, and ecological considerations, the study offers a comprehensive framework for decision-making. The inclusion of habitat suitability for indicator species ensures that the recommendations are grounded in ecological reality, addressing both biodiversity conservation and ecosystem functionality.

The E-Flow assessment in the Subarnarekha River underscores the significance of integrative methodologies combining hydrological, hydraulic, and ecological approaches. Employing hydrodynamic modelling tools like HEC-RAS and prioritizing indicator species ensures the development of scientifically robust flow recommendations. These findings support sustainable water resource management, aligning ecological conservation with socio-economic demands. Future research should integrate broader biodiversity assessments and stakeholder engagements to enhance the applicability of E-Flow frameworks. For holistic understanding of riverine ecosystems, the present methodology for E-Flow assessments in other river basins may be employed.

Keywords: *Environmental flow, indicators of hydrologic alteration, flow duration curves, HEC-RAS model, Subarnarekha River*

FOSTERING SOLUBILIZATION AND BIODEGRADATION OF OMPS USING THERMAL HYDROLYSIS PRETREATMENT

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Recently, sewage sludge (SS) has gained much attention as meritorious source rich in nutrients and trace elements, that can prove beneficial for soil repairment. Recovery, reuse and recycling of nutrients from SS along with synthesis of renewable energy source (biogas), at acceptable capital and operational costs has proved beneficial for ecosystem sustainability. Sewage sludge produced from wastewater treatment plants (WWTPs) is obligated to be disposed after proper treatment. However, its disposal has become as one of the critical issues associated with wastewater treatment plants. Our study emphasizes the effectiveness of thermal hydrolysis for sludge obtained from a sequencing batch reactor (SBR) system operating at a high solids retention time (SRT) of 40 days. Given the limited research on thermal hydrolysis of sludge regarding the fate of micropollutants and microbial diversity in digesters, this study aimed to evaluate the impact of thermal hydrolysis on: 1) sludge solubilization and methane production, 2) the removal of organic micropollutants, and 3) the microbial community structure within the digester. The thermal hydrolysis process (THP), an advanced steam explosion pretreatment, is primarily used to enhance sludge solubilization and boost methane production during downstream anaerobic digestion (AD). However, its effectiveness in treating high solids retention time (SRT) sludge, reducing emerging organic micropollutants, and its impact on the anaerobic microbial community remain uncertain. In this study, sludge from a sequencing batch reactor (SBR) operating at a 40-day SRT was subjected to THP at temperatures ranging from 120 to 180°C for 30 to 120 minutes. The effects of THP on organic solubilization, methane yield, organic micropollutant removal, and microbial community dynamics were investigated.

Dewatered sludge (20% TS) was collected from SBR-based STP at IIT Roorkee and was pretreated using CAMBI thermal hydrolysis at 6 bar pressure and at different temperatures and treatment time ranging from 120-180°C and 30-120 minutes. Both raw and thermally pretreated sludge samples were characterized for total solids (TS), volatile solids (VS), carbon to nitrogen ration (C/N), total phosphate (TP), total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), NH4-N, total alkalinity, total and soluble carbohydrates, total and soluble proteins, and, total and fecal coliforms. Tests for pH, total solids (TS), volatile solids (VS), total organic carbon (TOC) determination were conducted according to Standard Methods (APHA, 2017). HACH Nessler method (8075) was used to measure the ammonia. Proteins and carbohydrates were analysed by the conventional Lowry and anthrone reagent methods, respectively. For the isolation of OMPs, the solid-phase extraction method was employed using 200 mg OASIS HLB cartridges. The raw sludge and Cambi pretreated sludge (after AD) samples from each temperature with highest biogas yield were used for metagenomic and organic micropollutants characterization. For metagenomic analysis, 16s RNA sequencing was done using V3-V4 region primers.

Out of the THP tested conditions- 120-180°C for 30-120min, the best COD and Protein solubilisation of 40% and 37%, respectively, was achieved at 160°C/30minutes. The cumulative methane yield was 4 times higher in thermally pretreated sludge (507mL/gVS) in comparison to control (123 mL/gVS). VS reduction in CAMBI was 54% as compared to Control (21%). Cambi followed by AD also enhanced biodegradability of few organc micropollutants (OMPs) like Enrofloxacin, Ciprofloxacin, and Bezafibrate (>80% removal) and estrone, 17β-estradiol and diclofenac (50-70% removal). Within the bacterial domain, the most abundant phyla were Proteobacteria, Firmicutes, Chloroflexi, and Bacteroidetes, collectively accounting for >70–80% of bacterial reads. These phyla have been reported to dominate in anaerobic digesters treating sludge. Overall, THP enhanced anaerobic digestion, demonstrated superior performance compared to control digestion, with improved methane yields, higher volatile solids and micropollutant removal, and a more diverse microbial community in the digester. It improved biodegradability, biogas yield, pathogen annihilation, sludge solubilisation, high organic loading rate (OLR), dewaterability and energy recovery. Microbial community structure is a vital parameter for better performance of AD process. Thermal hydrolysis and typical anaerobic microbial consortium effectively mitigate organic micropollutants after AD.

Keywords: *CAMBI, solubilization, sewage sludge, thermal hydrolysis process, OMPs*

SYSTEM CHARACTERISTICS OF HIMALAYAN TRIBUTARIES OF UPPER GANGA BASIN, INDIA

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Climate change is altering the temporal and spatial distribution of different components of hydrologic cycle. Any change in the quality and quantity of the Himalayan tributaries of River Ganga under the climate change regime will impact the quality parameters of River Ganga. Some studies on the chemical characteristics of melt water discharged from glaciers indicate that chemical activity is more intense in these regions than in tropics. Altered flows in the rivers may change the habitat (depth, velocity, temperature, pH, DO, BOD, COD, sediment concentration) required for survival of various aquatic species. As these species are very important considering the fact that they are responsible for the self-purification capacity of the rivers. Hence, it becomes imperative to study the impact of climate change on the river ecology. River systems, generally regarded as 'pipes' play a crucial role in the global carbon cycle exporting carbon dioxide (CO_2) via the water-air interface to the atmosphere. Inland waters discharge about 0.9 Gt of carbon each year into the oceans. While only a small proportion of carbon entering a river network ultimately makes it to the ocean, increasing evidence suggests that a significant portion would be buried within the river network or released back into the atmosphere while en route. Rivers are hence considered sources of atmospheric carbon dioxide. The partial pressure or effective internal pressure of riverine CO_2, or pCO_2, is recognised as a significant factor in estimating CO_2 outgassing because it shows the gradient in river CO_2 concentration in relation to atmospheric equilibrium (i.e., 410 atm) and further reflects both biogeochemical processes and in situ carbon dynamics and in the watershed. Moreover, the complex pCO_2 dynamics in river waters are often driven by both internal and external environments involving physical, chemical, and biological factors. The $p(CO_2)$ signature of meltwater can be used to characterize different glacial hydrological weathering environments. When proton supply equals the consumption, the $p(CO_2)$ of the solution remains in the equilibrium with the atmosphere, the system is said to be open. If pCO_2 of solutions are not equal to atmospheric pCO_2 ($10^{-3.5}$atm), it can be said to be in disequilibrium with respect to the atmosphere. When the supply of protons is more than their consumption, then high $p(CO_2)$ conditions arise. Low $p(CO_2)$ conditions arise when the demand of protons for chemical weathering is more than the rate of CO_2 diffusion into the solution indicating closed system weathering.

In the present paper, the system characteristics of Gangotri glacier, the source of River Bhagirathi and River Alknanda were discussed. For Gangotri glacier, hydrochemical data of meltwater evolved during ablation period of the year 2014-2016 was used for the study and hydrochemical data of River Alaknanda evolved during the year 2016-2018 was used and hydrochemical analysis for different water quality parameters was performed as per standard methods prescribed in APHA. Gangotri glacier system is dominated by high $p(CO_2)$ closed system associated due to higher proton release from oxidation of sulphides and low $p(CO_2)$ closed system during the times of prolonged snow cover and under developed subglacial drainage system. The river chemistry is predominately controlled by chemical weathering with carbonation being the major proton-producing reaction. The pCO_2 values were

consistently higher than atmospheric levels, indicating a closed system with a substantial carbon dioxide contribution. Further, the Alaknanda River was identified as high-$p$$CO_2$ closed system. The observed trends in $p$$CO_2$ highlighted complex interactions between various factors, including flow dynamics, biological processes, and the influx of tributaries. The elevated $p$$CO_2$ levels further emphasize the river's role as a significant carbon dioxide source. The study showed the persistence of high $p$$CO_2$ closed system characteristics associated with increased suspended sediment concentration resulting from carbonate weathering, dominance of HCO_3^- over SO_4^{2-} and thereby results in high values of C ratio in River Alaknanda. The open and closed system characteristics based on $p$$CO_2$ levels reveals the influence of geochemical mechanisms and environmental factors on the river's carbon dioxide saturation. Understanding the open and closed system behaviour has important implications for aquatic ecosystems and water quality management. The persistence of high $p$$CO_2$ closed system conditions downstream can significantly impact aquatic ecosystems, potentially causing stress to aquatic organisms.

Keywords: *Hydrochemistry, pCO_2, open system, closed system, suspended sediment, C ratio*

ENVIRONMENTAL FLOW ASSESSMENT FOR YAMUNA RIVER, INDIA FROM HATHNIKUND BARRAGE TO OKHLA BARRAGE

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River Yamuna during non-monsoon season carries very less flow in its stretch from Hathnikund to Okhla barrage, which adversely affects the quantity and quality of water in the river. The assessment of e-flows for the study reach is based on integrated hydrodynamic and hydrological modelling using SWAT and HEC-RAS 1D models. A variety of datasets are required as model inputs as well as to validate the model outputs. Besides the river water quality, the study also investigates the variation in groundwater levels over a period of more than four decades. All such necessary data were collected from concerned agencies. In addition, exhaustive field surveys were carried out for the following: (1) identification of the indicator fish species and assessment of their habitat requirement-based investigations in the river, and (2) river cross-section surveys for a total of 306 lines at closely spaced intervals.

The analysis of depth to groundwater levels for pre-monsoon and post-monsoon over a period of four decades from 1975 to 2018 has revealed maximum depletion in water levels ranging from 10 to 20 m in the Mawi-Baghpat reach during the months of April and May. Receding groundwater levels have in turn affected the baseflow contribution to the flows in Yamuna. For the study reach, the ratio of baseflow to total river flow is found to be higher in the non-monsoon season than in the monsoon season. This pattern is representative of other gauges in the study reach and shows the importance of baseflows in sustaining river flows during non-monsoon period. Water quality analysis have shown that between the Wazirabad and Okhla barrage, the river receives approx. 6140 kg/hr BOD load out of which around 70% load is contributed through Nazafgarh drain. The average non-monsoonal DO value in this river stretch is 0.4±0.12 mg/l as O2. During the field surveys, the DO value in this stretch was non-detectable indicating the BOD load to the river higher than the assimilative capacity of the river. The water quality up to Wazirabad barrage is good for fish proliferation, however, the reduction in DO values downstream of Mawi is a cause for concern. Field surveys have revealed three major fish habitats types such as pools, riffles and runs at the sampling sites in Yamuna River. The identified indicator species, *Bangana dero* and *Raiamas bola* are thriving well in run habitat of channel with depth ranging from 60 to 90 cm and velocity in the range of 0.1 m/s. Hence, ensuring minimum water depth of 60 cm and velocity of 0.1 m/s at riffle/run habitat in the river will safeguard the fish diversity in Yamuna River.

The integrated hydrologic and hydrodynamic modeling approach has been adopted to assess the e-flows between Hathnikund barrage and Okhla barrage and to compute the releases required from Hathnikund barrage for maintaining these e-flows. For converting the habitat suitability depth values into the flow values, depth versus discharge curves have been developed at selected 13 locations covering the whole hydrologic regime using HEC-RAS simulations. Using the developed depth vs discharge curves for different sites, the minimum desirable flow values required for maintaining suitable physical habitat in terms of desirable flow have been estimated. The flows required to be released from Hathnikund barrage for maintaining the minimum desirable amount of flow at different sites during different seasons have been estimated using the flow series simulated by the calibrated hydrologic model SWAT. The releases required from Hathnikund barrage during a specific month is computed by taking the maximum of the releases estimated from Hathnikund barrage for meeting the minimum depth requirement of 0.60 m at 13 identified locations corresponding to the specific month.

For carrying out various functions, the aquatic ecosystem needs natural flow variability within the year, for its sustenance. Incorporation of natural variability of flows has been carried out by taking the minimum depth of 60 cm for the month of May (being the driest month at all the G&D sites downstream of Hathnikund barrage) and modifying the releases as per the existing natural variability as observed in long-term historical data. Final recommended releases from Hathnikund barrage for maintaining required habitat conditions between Hathnikund and Okhla barrage during different months of a year ranged from 23 to 220 cumec ranging from Jan to Aug have been estimated.

Keywords: *E-Flows, River ecosystem, keystone species, hydrodynamic modelling, hydrological modelling*

RESTORING OF POLLUTED RIVER STRETCHES IN TAMIL NADU: A STATUS AND STRATEGIC FRAMEWORK

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The water quality management in India is performed under the provision of the Water Act, 1974 and basic objective is to maintain and restore the wholesomeness of national aquatic resources by prevention and control of pollution. Increasing demand of water for human consumption, irrigation and growing industrial activities have the impact on the water quality of rivers due to declining flows in rivers and depleting water levels of subsurface resources. The discharge of untreated domestic sewage, unscientific disposal of municipal solid waste, and untreated or partially treated industrial effluents cause pollution in rivers. Under National Water Quality Monitoring Programme (NWMP), the Central Pollution Control Board (CPCB) in association with State Pollution Control Boards (SPCBs) is monitoring the water quality of rivers in India. The water quality data is analysed and the monitoring locations exceeding the water quality criteria parameter of BOD 3 mg/L are identified as polluted locations and the polluted locations in a continuous sequence are defined as polluted river stretches. In 2015 based on 2009 to 2012 data, the CPCB has identified 302 stretches across 275 rivers in India as polluted river stretches (PRS). This status report is being updated periodically. As per 2022 report, there are 311 PRS identified in 279 rivers in India, out of which 10 river stretches are located in Tamil Nadu State. In order to restore these rivers, the CPCB has prioritized the PRS based on the concentration of BOD from priority I to V. Accordingly, Priority-I refers to highly polluted river stretch which need immediate action and Priority-V refers to relatively less polluted stretch which need secondary attention. Priority-I: BOD exceeding 30 mg/L [standard for discharge of treated sewage and effluent into rivers for dilution] and all locations exceeding 6 mg/L on all occasions, Priority-II: BOD having 20-30 mg/L and all locations exceeding 6 mg/L on all occasions, Priority-III: BOD having 10-20 mg/L and all locations exceeding 6 mg/L on all occasions, Priority-IV: BOD in the range of 6-10 mg/L and Priority-V: BOD in the range of 3-6mg/L.

Thus the 10 PRS in Tamilnadu are classified as follows: Priority-I six stretches (i) Cauvery [Mettur to Mayiladuthurai, 200 km], (ii) Vasista [Manivilundhan to Thiyaganur, 10 km], (iii) Sarabanga [Thathayampatti to T. Konagapadi, 15 km], (iv) Thirumanimutharu [Salem to Papparapatti, 15 km], (v) Adyar [Tambaram to Nandanam, 30.1 km], (vi) Cooum [Avadi to Sathyanagar, 31.7 km], Priority-IV one stretch (i.e) Bhavani [Sirumugai to Kalingarayan 60 km], Prioirty-V three stretches (i) Amaravathi [Madathukulam to Karur 108 km], (ii) Palar [Kodaiyanchi to Marapattu, 16.3 km], (iii) Tamirabarani [Pappankulam to Arumuganeri 80 km]. These river stretches need to be restored to the primary water quality criteria for bathing wasters as prescribed in the Environment (Protection) Rules, 1986. As per the CPCB guidelines, Tamil Nadu Pollution Control Board (TNPCB) in association with line departments have prepared action plan for each PRS. The action plan covered identification of polluting sources including functioning status of sewage treatment plants (STPs), effluent treatment plants (ETPs), common effluent treatment plants (CETPs), solid waste management and processing facilities, quantification and characterization of solid waste, trade effluent from industries and sewage from local bodies generated in the catchment area

of polluted river stretch. The gaps identified is addressed with proposal for establishment of new STPs, solid waste processing facilities, and CETPs for industrial effluent. The action plan also addressed the issues relating to groundwater extraction, adopting good irrigation practices, protection and management of flood plain zones, rain water harvesting, groundwater charging, maintaining minimum environmental flow of river and plantation on both sides of the river. The plan also covered setting up of biodiversity parks on flood plains by removing encroachment as an important component for river rejuvenation. The plan also focused on proper interception and diversion of sewage carrying drains to the STP and emphasis on utilization of treated sewage so as to minimize extraction of ground or surface water. The action plan also has defined specific timelines for execution. The action plans are being implemented by the respective line departments and it is being monitored by the high-level committees from state and central governments. The TNPCB monitors the water quality of these river stretches at selected locations under NWMP on monthly basis and upload the data in their website. Parameters being monitored include fecal coliform, fecal streptococci, pH, DO, and BOD which are prescribed as primary water quality criteria for bathing waters.

As per the CPCB draft criteria for deletion of river stretches from the list of identified PRS, water quality data of the river stretch for all the locations should comply with primary water quality criteria for bathing waters at least consecutively for a period of two years. Accordingly, the level of fecal coliform should be <500MPN/100 mL, fecal streptococci <100 MPN/100mL, pH 6-5 to 8.5, DO >5mg/L and BOD <3 mg/L. The monitoring data of these 10 PRS for last two years (i.e. 2022 to 2023) are plotted in graph. From the plotted graphs, it is noted that in river Cauvery, 10 of the 19 monitored locations met bathing water standards in 2022, increasing to 17 locations in 2023. In river Bhavani, all seven monitored locations met the standards consistently in 2022 and 2023. Similarly, in river Tamirabarani, all 12 monitored locations met the standards in 2022, with slight deterioration in one location in 2023 when 11 locations complied with. The Palar River, monitored at a single location, met the standards for both years. However, Adyar and Cooum rivers failed to meet the standards across all the monitoring locations. The Vasista, Thirumanimutharu, and Sarabanga rivers, monitored at single location each, failed to meet the standards in both years. In Amaravathi River, out of three monitored locations, two locations achieved compliance in 2023. Based on these results, it is inferred that Bhavani, Tamirabarani, and Palar River stretches are in compliance with standards for bathing waters and hence eligible for removal from the PRS list. However, it is essential to ensure consistent compliance with the standards.

The data demonstrate that there is a significant improvement in water quality in river stretches of Bhavani, Tamirabarani, and Palar, which highlights efficacy of targeted restoration measures. However, Adyar, Cooum, and other Priority-I rivers calls for enhanced efforts. The successful restoration of PRS hinges on completion of proposed action plans, strict enforcement of pollution control regulations, and sustained monitoring. Intensified efforts are required to address the gap for management of sewage and solid waste by the local bodies. Public participation in river conservation and the adoption of community-driven initiatives are critical for long-term success. Advanced technologies for real-time water quality monitoring can help to identify challenges promptly and adopt management strategies as needed. The restoration of polluted river stretches is essential for ensuring sustainable development and fulfilling the SDG related to water.

Keywords: *Pollution, water quality, restoration strategies, sustainable development*

ASSESSING RIVER DISCHARGE PATTERNS FOR ECOSYSTEM SUSTAINABILITY: A CASE STUDY OF THE WAINGANGA RIVER

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Water is essential for sustaining life on earth and protecting environmental balance. Availability of water is prerequisite for various biological and ecological processes crucial for and ecosystems. Anthropogenic activities triggered significant harm to aquatic environments. To preserve and restore healthy river ecosystems, there is an urgent need for well-planned, seasonal, and year-round management strategies. Historical 30 years discharge data of the Wainganga River at the Satrapur gauging station were analyzed using Weibull's method to perform a probability analysis. The study identified three types of years: wet (Q10), normal (Q50), and dry (Q90). These three year types provided insights into the seasonal flow patterns and water availability of the river. To better understand seasonal variations, each year was divided into monsoon, winter, and summer seasons. Dry, normal, and wet years, the corresponding discharge rates were 625, 1763, and 4993 cubic meters per second (m^3/s). In a dry year, seasonal flows were recorded as 51.37 m^3/s during the monsoon, 7.10 m^3/s during the winter, and 0.76 m^3/s during the summer. In a typical (normal) year, flows were 144.47 m^3/s in the monsoon, 17.65 m^3/s in winter, and 5.01 m^3/s in summer. Higher fluctuations were observed in the wet years with monsoon flows of 342.79 m^3/s, winter flows of 120.64 m^3/s, and summer flows of 9.35 m^3/s. These seasonal and annual variations highlight the dynamic nature of the river and the challenges of managing water resources sustainably. They underscore the need for improved planning and water management strategies to maintain river ecosystems effectively.

Keywords: *Aquatic ecosystems, Wainganga River, Weibull's probability analysis, seasonal variations, sustainable water management*